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## **A novel approach of spreading spectrum in OFDM systems**

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### Abstract

A method for spectrum spreading in an orthogonal frequency division multiplexing (OFDM) system is proposed in this paper, resulting in a spread spectrum OFDM (SS-OFDM) system suitable for ultra-wideband (UWB) applications. By modifying the IFFT module in a conventional OFDM transmitter and interleaving the modulated signal samples within an OFDM symbol, the transmitted signal spectrum is spread greatly to realize spread spectrum communications. This method of spectrum spreading is also compared with that of the multiband OFDM (MB-OFDM) system. The SS-OFDM signal has the characteristics of a white noise, and its power spectrum density is constant within the desired bandwidth. One of the main advantages of the proposed system is that it can be used for UWB communication without the need for frequency hopping. In addition, the transmitted signal bandwidth can be selected flexibly to meet different system requirements.

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# A Novel Approach of Spreading Spectrum in OFDM Systems

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**Abstract**—A method for spectrum spreading in an Orthogonal Frequency Division Multiplexing (OFDM) system is proposed in this paper, resulting in a Spread Spectrum OFDM (SS-OFDM) system suitable for ultra-wideband (UWB) applications. By modifying the IFFT module in a conventional OFDM transmitter and interleaving the modulated signal samples within an OFDM symbol, the transmitted signal spectrum is spread greatly to realize spread spectrum communications. This method of spectrum spreading is also compared with that of the Multiband OFDM (MB-OFDM) system. The SS-OFDM signal has the characteristics of a white noise, and its power spectrum density is constant within the desired bandwidth. One of the main advantages of the proposed system is that it can be used for UWB communication without the need for frequency hopping. In addition, the transmitted signal bandwidth can be selected flexibly to meet different system requirements.

## I. INTRODUCTION

There are a number of methods of spreading frequency spectrum in spread spectrum communication systems. Basically, these methods include Direct Sequence Spread Spectrum (DS-SS), Frequency Hopping Spread Spectrum (FH-SS), Time Hopping Spread Spectrum (TH-SS), and combinations of these methods[1-2].

Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) is a scheme of multicarrier transmission for ultra-wideband (UWB) communication [3,8,10]. Under this scheme, the whole available UWB spectrum between 3.1-10.6 GHz is divided into 14 subbands, each of which has a bandwidth of 528MHz in compliance with the FCC UWB definition. Only the three lowest subbands are currently used to make a total bandwidth of more than 1.5 GHz. MB-OFDM was proposed into the IEEE 802.15.3a standardization task group for Wireless Personal Area Network (WPAN) applications. This task group has, however, been disbanded without agreeing on an UWB standard.

The MB-OFDM system employs the frequency hopping technique to spread its signal spectrum[3]. That is, it firstly places a OFDM symbol with 528MHz bandwidth on a subband for a short time interval (312.5 ns), then moves the successive OFDM symbols onto different subbands according to a time-frequency code, so that the signal spans a bandwidth of more than 1.5GHz over 3 subbands. Within each subband, the 528MHz bandwidth is split into a number of narrow bands called subcarriers as in a conventional OFDM system. However, the use of frequency hopping increases the complexity

of the MB-OFDM transceiver's RF front-ends, and causes transmitting power compliance concerns. The conventional OFDM modulation also affects its power efficiency due to the problem of large peak-to-average power ratio[4-5].

The proposed SS-OFDM system employs interleaving technique to place the respectively modulated signal samples for different subcarriers at different time instants instead of superimposing them together. Hence, the SS-OFDM signal has a bandwidth much wider than that of the conventional OFDM signal. In addition, the signal has the characteristics of a white noise and its power spectrum density is constant. This system can also distinctively reduce the peak-to-average power ratio of the transmitted signal, which is further advantageous over the MB-OFDM system.

This paper focuses primarily on the transceiver architecture of the SS-OFDM system. It is organized as follows. Section II discusses the fundamental principles of spread spectrum communications. Section III describes the transceiver algorithms for generating and receiving SS-OFDM signals. The temporal and spectral characteristics of the SS-OFDM signals are given. Simulated performance of the SS-OFDM receiver is also presented in this section. Finally, conclusions are drawn in Section IV.

## II. DESIGN PRINCIPLE OF SS-OFDM SYSTEM

The fundamental theory of spread spectrum system can be described by Shannon's channel capacity formula  $C = W \log(1 + \frac{P_S}{P_N})$ , where  $W$  is the signal bandwidth,  $P_S$  the signal power and  $P_N$  the noise power[6]. This formula indicates that when the signal to noise ratio of the transmission system drops in a Gaussian channel, the channel capacity can remain unchanged by increasing the transmission bandwidth  $W$ .

Shannon's theory also indicates that with Gaussian noise interference present, the optimum signal for practical reliable communication is the signal with the statistical characteristics of a white noise in the limited mean power channel. The power spectral density of a white noise is

$$\Phi(\omega) = \frac{N_0}{2} \quad -\infty < \omega < \infty \quad (1)$$

where  $N_0$  is the single-sided power spectral density, and its

autocorrelation function is

$$\varphi(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi(\omega) e^{j\omega\tau} d\omega = \frac{N_0}{2} \delta(\tau) \quad (2)$$

where

$$\delta(\tau) = \begin{cases} 1, & \text{for } \tau = 0 \\ 0, & \text{elsewhere} \end{cases} \quad (3)$$

Equ. (2) means that the autocorrelation function of a white noise is an impulse function. According to this property, the signal transmitted on the AWGN channel should be designed so that its autocorrelation function is an impulse function,

It has been also proved theoretically that to overcome multipath interference the optimum transmitted signal is also a signal with the statistical characteristics of a white noise[7].

We will show in the following section that the transmitted SS-OFDM signal satisfies the above signal design criteria.

### III. ARCHITECTURE AND ALGORITHM OF SS-OFDM TRANSCIVER

#### A. Method of Spectrum Spreading in MB-OFDM System

In order to understand the algorithm of spectrum spreading in the SS-OFDM system, we firstly describe the method of spectrum spreading in the MB-OFDM system for comparison purpose. Fig.1 shows the architecture of the MB-OFDM transmitter [9]. We can see that the MB-OFDM system needs two steps to implement the spectrum spreading. The first step is the Inverse Fast Fourier Transform (IFFT) which is used to modulate multiple subcarriers and multiplex them to form wideband signals. The second step is the frequency hopping which is employed to move the signal to different frequency bands to realize ultra-wideband communication. The QPSK symbols modulate the orthogonal sinusoidal subcarriers using the IFFT to form the OFDM symbol in the time domain. These modulated signal samples for different subcarriers are summed together to form the OFDM symbol. If we denote QPSK symbols by  $b_k$ , the number of the subcarriers by  $N$ , and the corresponding subcarrier frequency by  $f_k$ , where  $0 \leq k \leq N-1$ , MB-OFDM signal has the following expression

$$\begin{aligned} x(n) &= \frac{1}{N} \sum_{k=0}^{N-1} b_k e^{j2\pi f_k n} \\ &= \frac{1}{N} \sum_{k=0}^{N-1} b_k e^{j2\pi \frac{k}{N} n} \quad 0 \leq n \leq N-1. \end{aligned} \quad (4)$$

Letting  $W_N$  denote  $e^{-j2\pi/N}$ ,  $W_N^{-nk}$  means the  $k^{th}$  subcarrier at  $n^{th}$  time instant. After the IFFT operation,  $N$  OFDM symbol samples are generated. For the convenience of description, we ignore the factor  $\frac{1}{N}$  thereafter. These  $N$  samples can be expressed in the matrix form

$$\begin{pmatrix} x(0) \\ x(1) \\ \vdots \\ x(N-1) \end{pmatrix} =$$

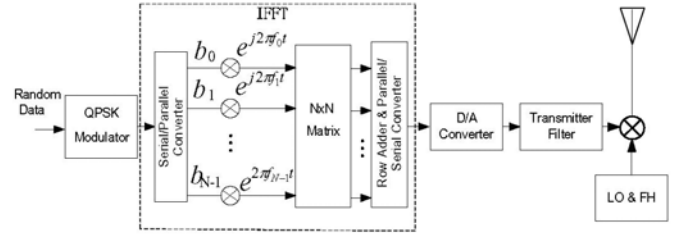


Fig. 1. Transmitter architecture of MB-OFDM.

$$\begin{pmatrix} b_0 W_N^0 + b_1 W_N^{0*1} + \dots + b_k W_N^{0*(N-1)} \\ b_0 W_N^{-1*0} + b_1 W_N^{-1*1} + \dots + b_k W_N^{-1*(N-1)} \\ \vdots \\ b_0 W_N^{-(N-1)*0} + b_1 W_N^{-(N-1)*1} + \dots + b_k W_N^{-(N-1)*(N-1)} \end{pmatrix} \quad (5)$$

The sequence  $[x(0), x(1), \dots, x(N-1)]$  is an OFDM symbol after IFFT operation. After the D/A converter and transmitter filter, the analogue baseband signal is generated. Then the system shifts the baseband signal to a particular frequency band for a short time interval using frequency hopping. The signal hops between different frequency bands, so that it spans a range of spectrum over a period of time[5], and the bandwidth reaches 1.584GHz. Each OFDM symbol consists of many non-zero subcarriers within the symbol interval. Its spectrum can be regarded as the convolution of the spectrum of a window pulse with a group of subcarriers. The spectra of the respectively modulated data symbols are overlapped. At the centre of each subcarrier, all the spectrum values of other subcarriers are zero. In this way, the spectrum efficiency can be increased. However, with the carrier frequency hopping in different subbands, the signal power is not evenly distributed across the subbands, which leads to some problems with power allocation. The symbol rate and the shape of power spectral density of the modulated signal depend on the rate at which the symbols enter the D/A converter and the transmitter filter. The signal transmission is not performed continuously on the 3 subbands. Instead, it is time multiplexed using frequency hopping between different subbands. Therefore, the system has some challenging issues regarding system performance.

#### B. Transmitter Architecture and Algorithm of SS-OFDM System

Our aim is to design the OFDM symbols to fit the statistical characteristics of a white noise process which covers a wide range of frequencies at the same time, so that the disadvantages of the frequency hopping can be avoided. The transmitter structure of the SS-OFDM system is displayed in Fig.2. The OFDM modulation is implemented by modifying the IFFT module. Firstly, the random data are fed into the QPSK modulator to form complex QPSK symbols. After serial to parallel conversion, each QPSK symbol is allocated to a different subcarrier. Each subcarrier is modulated by the respective QPSK symbol. The modulated subcarriers are stored in memory as an  $N \times N$  matrix and then interleaved in the time domain, instead of summing the  $N$  modulated subcarriers together. We can describe the process of generating

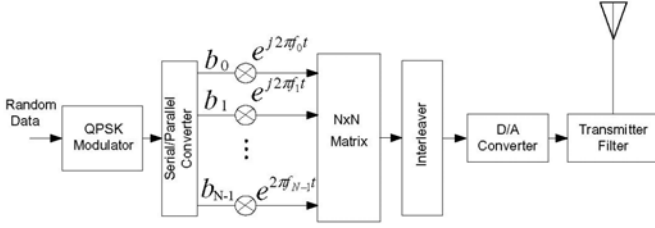


Fig. 2. Transmitter architecture of SS-OFDM.

the  $N \times N$  SS-OFDM sample matrix as follows. Assume that there are  $N$  orthogonal subcarriers employed in the SS-OFDM system and the OFDM symbol duration is  $T$ . The modified IFFT module will result in a  $N \times N$  sample matrix. Each row of the matrix corresponds to  $N$  samples from different modulated subcarriers. That means that within an OFDM symbol duration there are  $N \times N$  samples generated.

Let us examine the  $N \times N$  sample matrix. We still use  $b_k$  to denote the  $N$  QPSK symbols. The  $N$  orthogonal subcarriers are exactly the same as that described above. After we perform OFDM modulation on the input QPSK symbols, the output matrix becomes an  $N \times N$  square matrix which can be expressed as follows

$$\begin{pmatrix} x_{0,0} & x_{0,1} & \cdots & x_{0,N-1} \\ x_{1,0} & x_{1,1} & \cdots & x_{1,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N-1,0} & x_{N-1,1} & \cdots & x_{N-1,N-1} \end{pmatrix} = \begin{pmatrix} b_0 W_N^0 & b_1 W_N^{0*1} \cdots b_{N-1} W_N^{0*(N-1)} \\ b_0 W_N^{-1*0} & b_1 W_N^{-1*1} \cdots b_{N-1} W_N^{-1*(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ b_0 W_N^{-(N-1)*0} & b_1 W_N^{-(N-1)*1} \cdots b_{N-1} W_N^{-(N-1)*(N-1)} \end{pmatrix}$$

Let us compare the two equations (5) and (6). These two equations are expressions of the results of OFDM modulation in the MB-OFDM and SS-OFDM systems, respectively. In equation (5), the OFDM modulation results are summed up and  $N$  OFDM samples are formed. In equation (6), the OFDM modulation outputs are not superimposed. Instead, they will be interleaved according to different interleaving algorithms.

If we rearrange the input  $N$  QPSK symbols into a diagonal matrix and pad zeros in the spare spaces to form a square matrix, i.e.,

$$Diag(b) = \begin{pmatrix} b_0 & 0 & \cdots & 0 \\ 0 & b_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & b_{N-1} \end{pmatrix}$$

equation (6) can be rewritten as follows.

$$\begin{pmatrix} x_{0,0} & x_{0,1} & \cdots & x_{0,N-1} \\ x_{1,0} & x_{1,1} & \cdots & x_{1,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N-1,0} & x_{N-1,1} & \cdots & x_{N-1,N-1} \end{pmatrix}$$

$$= [W_N^{-nk}] * Diag(b_k) =$$

$$\begin{pmatrix} W_N^{0*0} & W_N^{0*1} & \cdots & W_N^{0*(N-1)} \\ W_N^{-1*0} & W_N^{-1*1} & \cdots & W_N^{-1*(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ W_N^{-(N-1)*0} & W_N^{-(N-1)*1} & \cdots & W_N^{-(N-1)*(N-1)} \end{pmatrix} * \begin{pmatrix} b_0 & 0 & \cdots & 0 \\ 0 & b_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & b_{N-1} \end{pmatrix}. \quad (6)$$

where  $[W_N^{-nk}]$  is the original IFFT matrix. We can see that equ. (7) produces the required results.

After the  $N \times N$  sample matrix is generated, we then use the interleaving operation to produce the  $N \times N$  samples of the SS-OFDM symbol. Different interleaving algorithms such as pseudo random interleaving, periodic interleaving and convolutional interleaving can be employed[11].

After interleaving, the samples in the matrix are taken out one by one according to the order of columns or rows. That is to say,  $N \times N$  samples come out during an OFDM symbol duration  $T$ . The sampling rate is  $N$  times higher than that of the conventional OFDM system with the same number of subcarriers. The example in-phase and quadrature waveforms of the OFDM sample are plotted in Fig. 3 which shows the first 250 samples of the  $32 \times 32$  samples of one SS-OFDM symbol. Note that the first 32 samples are 32 input QPSK symbols themselves. The second 32 samples are the 32 input QPSK symbols with respective phase rotations defined by the second row of the IFFT matrix. In general, each segment of 32 samples is the 32 QPSK symbols rotated by respective phases defined by the corresponding row in the IFFT matrix. We also see from Fig. 3 that the envelope of the SS-OFDM symbol is constant. Due to the increase of the SS-OFDM sampling rate which is  $N$  times higher than that of conventional OFDM, the spectrum has been spread  $N$  times. We can also verify that the SS-OFDM symbol has an impulse autocorrelation in discrete-time domain and its power spectrum density is constant before D/A.

Fig. 4 displays the spectrum of SS-OFDM signal after D/A. Since the signal spectrum is widely spread already there is no need for frequency hopping any more to achieve spectrum spreading. We only need to use appropriate transmitter filter to select the required bandwidth. Two different frequency responses designed by adjusting the parameters of a raised cosine filter are illustrated in Fig. 4. We can choose different bandwidths of the transmitted signals to meet different system requirements. Therefore, a signal with white noise characteristics provides great flexibility for SS-OFDM system design.

### C. SS-OFDM Receiver Architecture and Algorithm

In order to recover the transmitted data information, inverse operations are performed at the receiver. Assuming an AWGN



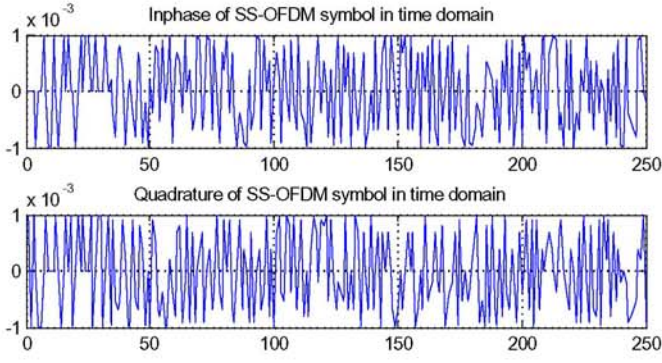


Fig. 3. Waveforms of SS-OFDM samples in time domain.

channel, Fig.5 illustrates the receiver architecture of the SS-OFDM system. It consists of receiver filter, A/D converter, de-interleaver, combiner, FFT module, parallel/serial converter and QPSK de-modulator.

The receiver filter can be designed to match the transmitter filter. The demodulation for the SS-OFDM system can not use the FFT operation directly before the received signals are processed. Since the transmitted signals are not superimposed after the IFFT at the transmitter, samples equal to the FFT size must be summed up before using the FFT operation at the receiver. After de-interleaving, received signal samples are the sequences,  $x_{0,0}, x_{0,1}, \dots, x_{0,N-1}, x_{1,0}, x_{1,1}, \dots, x_{1,N-1}, \dots, x_{N-1,0}, x_{N-1,1}, \dots, x_{N-1,N-1}$ . in an SS-OFDM symbol. In order to use FFT computation to demodulate the data symbols, we need to take out blocks of the samples equal to the FFT size to construct a  $N \times N$  matrix as:

$$X = \begin{pmatrix} x_{0,0} & x_{0,1} & \cdots & x_{0,N-1} \\ x_{1,0} & x_{1,1} & \cdots & x_{1,N-1} \\ \cdots & \cdots & \cdots & \cdots \\ x_{N-1,0} & x_{N-1,1} & \cdots & x_{N-1,N-1} \end{pmatrix}$$

If the samples in a row are added together, the matrix becomes a vector which is exactly the same as the FFT input vector in conventional OFDM demodulation and the FFT computation can be used to demodulate the SS-OFDM symbols. The process can be expressed in equ. (8).

$$\begin{pmatrix} x_{0,0} + x_{0,1} + \cdots + x_{0,N-1} \\ x_{1,0} + x_{1,1} + \cdots + x_{1,N-1} \\ \cdots \\ x_{N-1,0} + x_{N-1,1} + \cdots + x_{N-1,N-1} \end{pmatrix} = \begin{pmatrix} b_0 W_N^0 + b_1 W_N^{0*1} + \cdots + b_{N-1} W_N^{0*(N-1)} \\ b_0 W_N^{-1*0} + b_1 W_N^{-1*1} + \cdots + b_{N-1} W_N^{-1*(N-1)} \\ \cdots \\ b_0 W_N^{-(N-1)*0} + b_1 W_N^{-(N-1)*1} + \cdots + b_{N-1} W_N^{-(N-1)*(N-1)} \end{pmatrix} \quad (7)$$

$$= \begin{pmatrix} W_N^0 & W_N^{0*1} & \cdots & W_N^{0*(N-1)} \\ W_N^{-1*0} & W_N^{-1*1} & \cdots & W_N^{-1*(N-1)} \\ \cdots & \cdots & \cdots & \cdots \\ W_N^{-(N-1)*0} & W_N^{-(N-1)*1} & \cdots & W_N^{-(N-1)*(N-1)} \end{pmatrix} * \begin{pmatrix} b_0 \\ b_1 \\ \cdots \\ b_{N-1} \end{pmatrix} \quad (7)$$

The above analysis is for AWGN channel only. If the channel is not Gaussian, we need to estimate the channel first, and then use a different combining process. However, this is beyond the scope of this paper.

#### D. Simulation Results

In this section, we use numerical simulations to compare the performance of the SS-OFDM system with the theoretical one. All the simulation results are obtained under the assumption of complete synchronization between the receiver and transmitter. We set the FFT size as 128, 64, 32, 16, 8 and the corresponding number of subcarriers as 122, 58, 30, 14, 6 respectively. By setting different parameters of the FFT size and subcarriers, we obtain several kinds of results.

The simulation results indicate that the BER versus SNR curves are very similar to each other under different system parameters. Fig. 6 shows the theoretical BER performance for QPSK modulation and the simulated BER performance of the SS-OFDM system, respectively. The curve plotted with mark “\*” indicates the theoretical performance and the curve plotted with mark “o” displays the simulated performance.  $E_b/N_0$  denotes the ratio of bit energy to noise power spectral density, in dB.

The simulated performance results of the SS-OFDM system are plotted when the FFT size is set to 32 and the subcarriers to 32.  $E_b/N_0$  varies from -6dB to 8dB. We can see that the BER performance matches the desired performance.

#### IV. CONCLUSIONS

By simulation we show that the SS-OFDM system has the desired performance in terms of BER versus  $E_b/N_0$ . Since the signal spectrum covers a wide bandwidth, the SS-OFDM does not need frequency hopping for spreading spectrum. Due to the statistical characteristics of a white noise process, it can realize effective ultra-wideband communication. The transmitted bandwidth can be also selected flexibly, making it suitable for various communication systems under different circumstances. We can take advantages of the wide bandwidth characteristics of the signal to control the received signal bandwidth by designing matched filters using a pair of raised cosine filters. The simulation results indicate that the theoretical curves and the simulation curves match well. This indicates that the algorithm of spreading spectrum in the SS-OFDM system provides desired performance. For future work, we will consider practical multipath channel and research on effective combining and equalization techniques.

## V. ACKNOWLEDGEMENT

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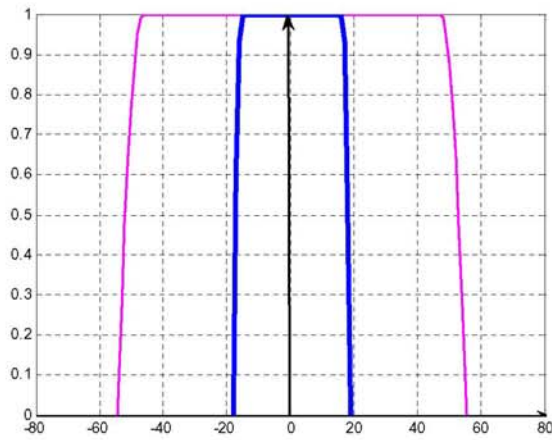


Fig. 4. Spectrum of SS-OFDM with different bandwidth filter.

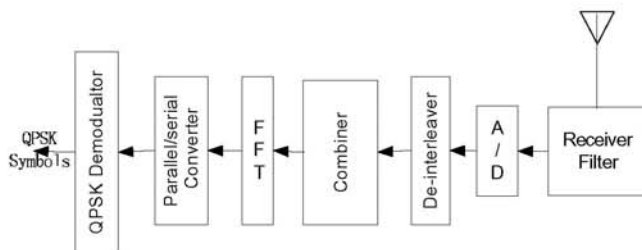


Fig. 5. Receiver structure of SS-OFDM system.

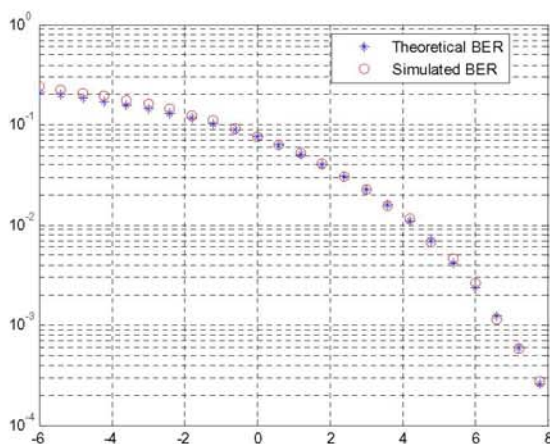


Fig. 6. Comparison between theoretical and simulated performance.